6. THERMAL ANALYSIS OF THE GENERIC CASKS IN A LONG DURATION FIRE

6.1 Introduction

Thermal analyses were performed on the four generic casks defined in Section 4. The analyses examined two fire environments, a 1000°C extra-regulatory fire environment and an 800°C regulatory fire environment. Both fires were assumed to be fully engulfing and optically dense. The analyses were performed with PATRAN/PThermal, a commercial heat transfer code [6-1], that includes the conduction, convection and radiation heat transfer modes. The casks were modeled as one-dimensional (1-D) axisymmetric cylinders, including a neutron shield. The heat that would be released to the cask interior by the decay of radionuclides in the spent fuel that each cask would be carrying was treated as an internal heat source.

6.2 Generic Casks Modeled

Figures 6.1 through 6.4 present schematic drawings of the four generic casks modeled in these analyses. The two generic truck casks modeled were a steel-lead-steel cask (Figure 6.1) and a steel-DU-steel cask (Figure 6.2), where DU refers to depleted uranium. The rail casks modeled were a steel-lead-steel cask (Figure 6.3) and a monolithic steel cask (Figure 6.4). These casks have dimensions similar to currently available casks, but have not been optimized for their thermal properties for any particular fuel load. Figure 6.5 presents a radial cross section at the center of these generic casks. The dimensions of these four generic casks, including the thicknesses of the four shells labeled A, B, C, and D in Figure 6.5, are given in Table 6.1. The maximum number of fuel assemblies assumed to be shipped in each cask is given in Table 6.2.

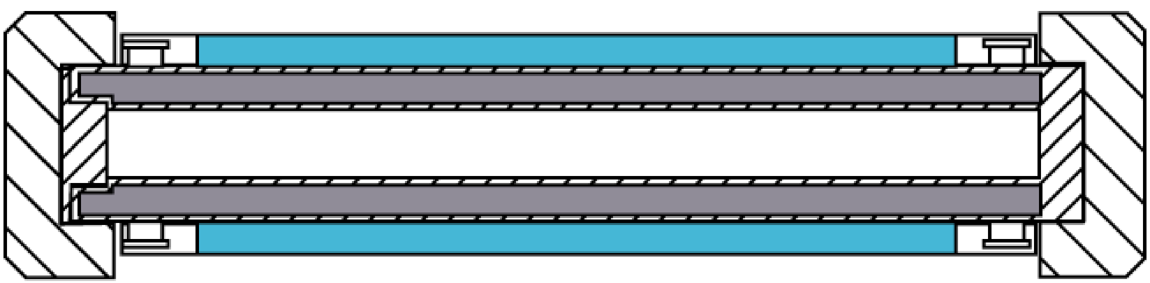

Figure 6.1 A generic, steel-lead-steel truck cask.

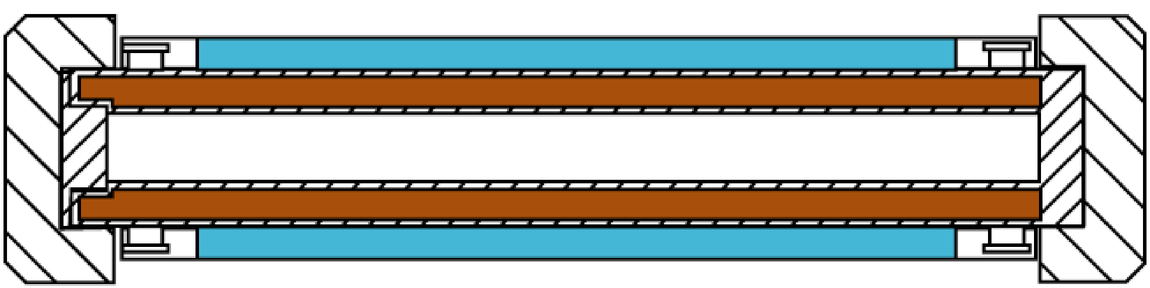

Figure 6.2 A generic, steel-DU-steel truck cask.

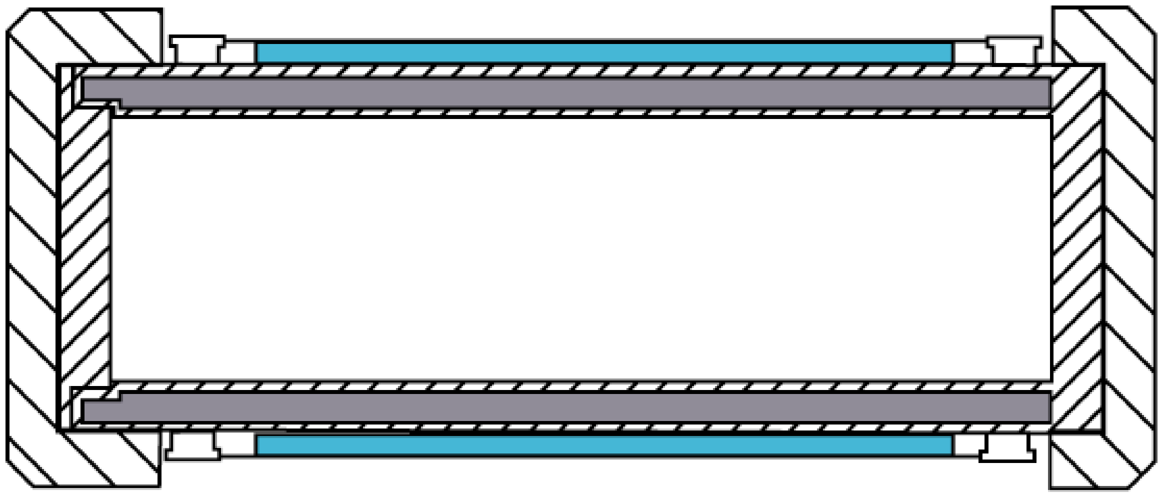

Figure 6.3 A generic, steel-lead-steel rail cask.

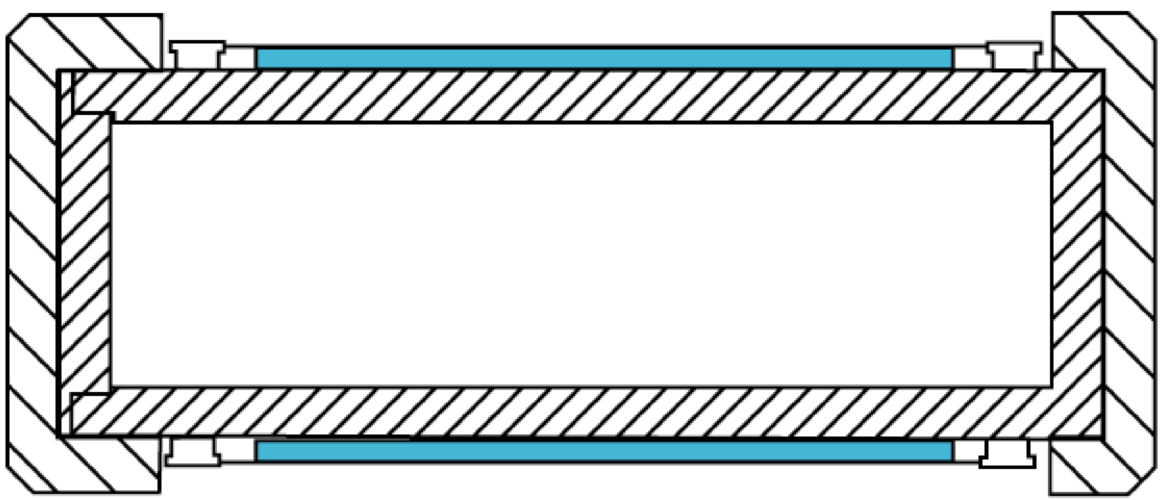

Figure 6.4 A generic, monolithic steel rail cask.

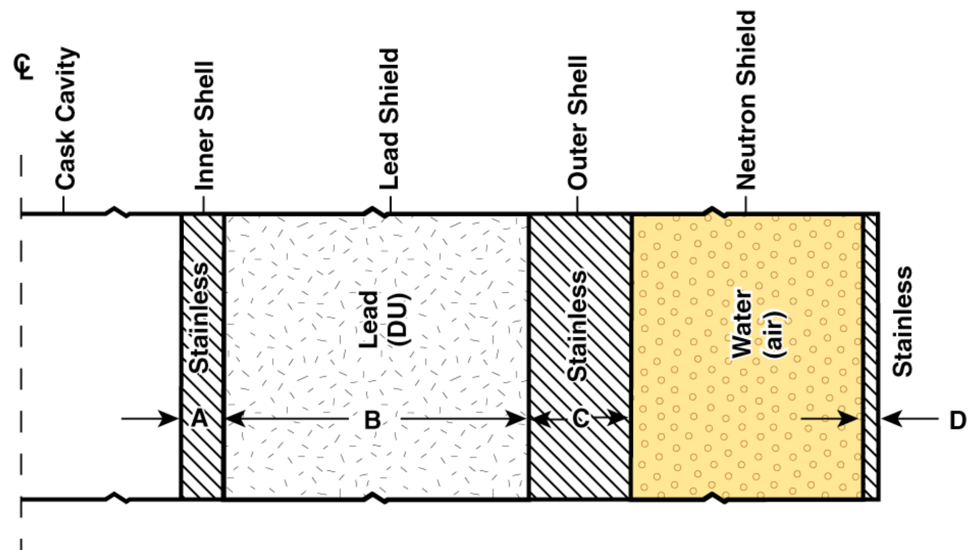

Figure 6.5 Generic wall cross section used in the 1-D axisymmetric, thermal modeling.

Table 6.1 Generic Cask Dimensions (m)

Cask	Wall Thicknesses A	Wall Thicknesses B	Wall Thicknesses C	Wall Thicknesses D	Neutron Shield Thickness	Outside Diameter	Cavity Diameter	Cask Length
Steel-Lead-Steel Truck Cask	0.0127 (0.5”)	0.1397 (5.5”)	0.0254 (1”)	0.006 (0.25”)	0.114 (4.5”)	0.94 (37”)	0.343 (13.5”)	5.207 (205”)
Steel-DU-Steel Truck Cask	0.0127 (0.5”)	0.0889 (3.5”)	0.0229 (0.9”)	0.006 (0.25”)	0.114 (4.5”)	0.953 (37.5”)	0.457 (18”)	5.08 (200”)
Steel-Lead-Steel Rail Cask	0.0254 (1”)	0.1143 (4.5”)	0.0508 (2”)	0.006 (0.25”)	0.114 (4.5”)	2.273 (89.5”)	1.651 (65”)	5.08 (200”)
Monolithic Steel Rail Cask	0.254 (10”)			0.006 (0.25”)	0.114 (4.5”)	2.4 (94.5”)	1.651 (65”)	4.826 (190”)

Table 6.2 Assumed Loading of PWR and BWR Assemblies for the Generic Casks

Cask	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Monolithic Steel	Steel-Lead-Steel
PWR	1	3	24	24
BWR	2	7	52	52

6.3 PATRAN/PThermal Model

The thermal effects of a long duration, external fire conditions on the casks were modeled in 1-D with an axisymmetric model (see Figure 6.5). The simulations were done in two steps. First, a steady-state simulation of the cask with its internal heat load from the fuel assemblies was done to obtain initial conditions for the analysis. A transient analysis in the presence of a long duration fire was then completed.

In the first stage, the neutron shield was assumed to be filled with water. Ambient temperature was set at 38°C. The internal heat load in each cask, generated by the decay of radionuclides in the spent fuel as calculated by ORIGEN [6-2], was set to the value presented in Table 6.3. Note that the generic casks are similar to modern casks designed for ten-year-old, moderate-burn-up fuel. This heat load was modeled as a flux onto the internal surface of each cask. Heat deposited in the inner shell of the cask by this heat flux was transferred by conduction in the solid shells of the cask, by conduction and convection in the water in the cask's neutron shield compartment, and by convection [6-3] and radiation in the air surrounding the cask. Thermal radiation was calculated with the gray-body approximation. In all cases, a cask outer surface emittance of 0.8 and a fire emittance of 0.9, consistent with 10 CFR 71 and at the high end of the normal range of surface emittances, were assumed. Thermal radiation across the neutron shield interior, when empty, was calculated using a typical stainless steel surface emittance of 0.5. Conduction and convection in the neutron shield water was modeled with a convection correlation that provided an effective value for conductivity in the water [6-4]. This model provided a steady state temperature profile in the cask characteristic of normal conditions of transport.

Table 6.3 Internal Heat Loads for Each of the Generic Casks for Three-Year-Old High Burnup Spent Fuel

Fuel Type	Assembly Heat Load	Rail Casks		Truck Casks	
		Monolithic Steel	Steel-Lead-Steel	Steel-Lead-Steel	Steel-DU-Steel
PWR	2796 W	67104 W (2289 W/m^2)	67104 W (2190 W/m^2)	2796 W (482 W/m^2)	8388 W (1100 W/m^2)
BWR	902.5 W	46930 W (1600 W/m^2)	46930 W (1532 W/m^2)	1805 W (312 W/m^2)	6318 W (828 W/m^2)

The temperature profile from the steady state calculation was used as a starting point for a transient calculation for the cask in the presence of an engulfing, optically dense, long duration fire. In the transient calculation, the water was replaced with air, the ambient temperature was increased from 38°C to 1000°C over one minute and held at 1000°C for 11 hours. Heat transfer to the outer surface of the cask from the fire was calculated with convection and radiation, through the air in the empty neutron shield compartment with conduction and radiation, and through the cask shells to the interior surface of the cask by conduction. All of the calculations used PWR decay heat loads, because these loads represent a conservative upper limit for the heat flux from spent fuel to the cask's internal surface.

6.4 Thermal Modeling Results

The PATRAN/PThermal analyses of the four generic casks determined the initial internal and external temperatures of the cask shell during normal transport conditions and the temperature response of the casks during a long duration, engulfing, optically dense fire.

6.4.1 Cask Initial Temperature Profiles

The steady state calculations determined the temperature profiles of the casks during the normal conditions of transport. The temperatures of the internal and external cask surfaces calculated for normal transport conditions are given in Table 6.4.

Table 6.4 Internal and External, Steady State, Cask Surface Temperatures

Cask	Internal	External
Steel-Lead-Steel Truck	72°C	69°C
Steel-DU-Steel Truck	113°C	104°C
Monolithic Steel Rail	215°C	193°C
Steel-Lead-Steel Rail	218°C	194°C

These temperatures are calculated for the generic casks that were not optimized for the postulated thermal loading, and therefore do not meet the surface temperature requirements of 10 CFR 71.43g. However, these temperatures do represent a conservative set of baseline cask temperatures for the purposes of this analysis.

6.4.2 Thermal Response to a Long Duration, 1000°C Fire

Figure 6.6 presents the time-dependent temperature change of the interior surface of each of the four generic casks while the cask is exposed to a long-duration, engulfing, optically dense 1000°C fire. Changes in the slopes of these temperature curves occur because of internal phase transitions in carbon steel (at 770°C) and depleted uranium (at 667°C and 775°C) and the melting of lead (at 327.5°C).

The times to reach the following three characteristic temperatures are of interest: 350°C where the rate of thermal degradation of elastomeric seals becomes significant, 750°C where spent fuel rods can fail by burst rupture, and 1000°C where the cask has come into equilibrium with the fire. The choice of the seal degradation and rod-burst temperatures is discussed in detail in Section 7. The times at which the casks reach these temperatures when heated continuously by an engulfing, optically dense, 1000°C fire are given in Table 6.5. Note that, because of thermal lags, some cask temperatures would continue to rise if the fire went out at each of these times.

The times required to reach the indicated temperatures at the inside surface of the inner shell, as shown in Figure 6.6, were used in Section 7.0 to estimate the probability of seal degradation and rod burst during cask exposure to long duration hydrocarbon fueled fires. The temperature of the inner surface of the cask body was used as an indicator of seal and rod response to heating in a fire for several reasons. First, inspection of the results of these calculations indicates that, when heated by a fire, temperatures in the lead or depleted uranium gamma shield are similar to, though usually 10 to 20°C hotter than, the temperature of the cask's inner surface. Second, although seal location is dependent on cask design, seal well temperatures are also expected to closely track cask inner surface temperatures. Thus, because a somewhat low seal degradation temperature of 350°C was chosen, the uncertainty in the time to reach seal degradation temperature is expected to be conservative, i. e., shorter than actual. Moreover, inspection of the probability distributions for fire duration presented in Tables 7.26 and 7.27 indicate, as is discussed below, that risk estimates will not be very sensitive to this choice. Through similar arguments, fuel rod bundle temperatures are also expected to closely track the temperature of the inside surface of the cask, although for "hot" fuel, the inner-fuel-assembly temperatures could be significantly higher. However, the assumption is made that this temperature should be a reasonable surrogate for average spent fuel rod temperatures.

There are four characteristic fire duration times of interest in a risk analysis: 10 minutes—the duration of a typical automobile fire, 30 minutes—the duration of a regulatory fire, 60 minutes—the typical duration of an experimental pool fire with fuel from one tanker truck, and 400 minutes—the typical duration of an experimental pool fire with fuel from one rail tank car. Table 6.6 presents the temperatures reached by each of the generic casks at these times in a long duration 1000°C fire.

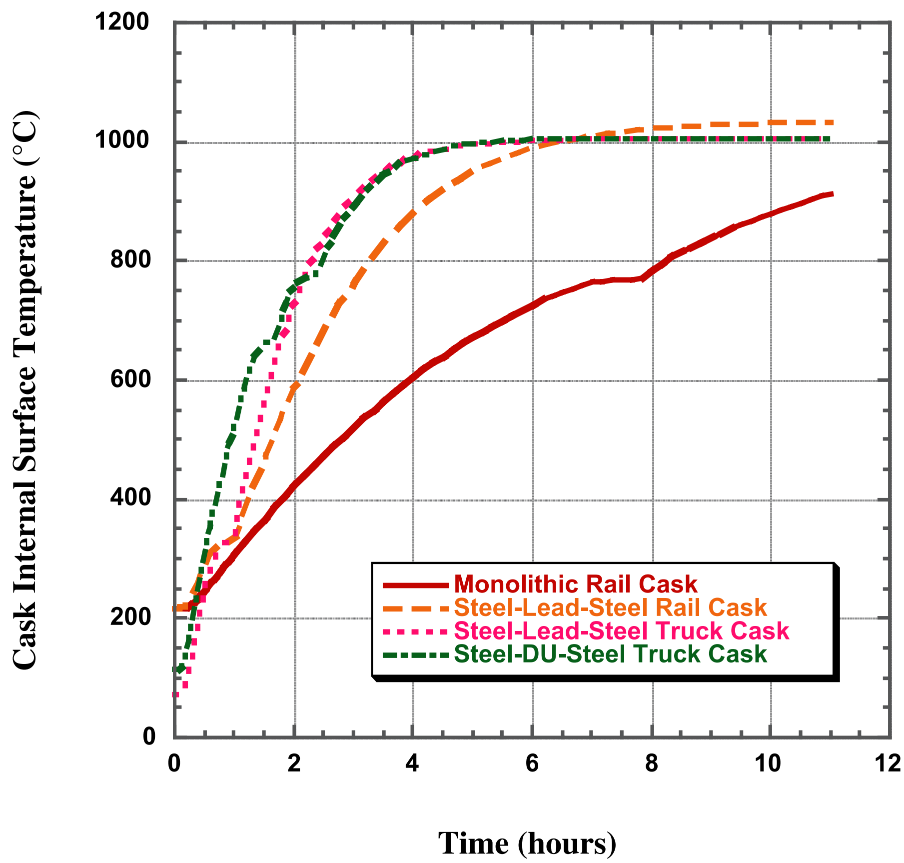

Figure 6.6 Internal surface temperature histories of the generic casks in an 1000°C long duration fire.

Table 6.5 Time (hours) Required for the Generic Cask Internal Surface to get to the Three Characteristic Temperatures in a Long Duration Engulfing, Optically Dense, 1000°C Fire.

Temperature (°C)	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
350	1.04	0.59	1.06	1.37
750	2.09	1.96	2.91	6.57
1000	5.55	5.32	6.43	>11

Table 6.6 Cask Internal Surface Temperatures (°C) for Four Characteristic Times in a Long Duration, Engulfing, Optically Dense, 1000°C Fire.

Time (minutes)	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
10	91	139	222	222
30	252	313	275	230
60	337	531	338	300
400	1000	1000	1000	750

6.4.3 Thermal Response to a Long Duration 800°C Fire

The regulatory requirements specify that thermal cask analysis be done with an 800°C fire. The response of the generic casks to an 800°C fire is given here for comparison. Table 6.7 lists the time required for the interior surface of each generic cask to climb to 350°C and 750°C in the 800°C fire and Table 6.8 presents the interior surface temperatures reached in that fire at each of the four characteristic times.

Table 6.7 Time (hours) Required for the Generic Cask Internal Surface to get to the Two Characteristic Temperatures in a Long Duration Engulfing, Optically Dense, 800°C Fire.

Temperature (°C)	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
350	1.77	1.06	1.69	2.37
750	4.88	5.07	6.32	>11

Table 6.8 Cask Internal Surface Temperatures for Four Characteristic Times in a Long Duration Engulfing, Optically Dense, 800°C Fire.

Time (minutes)	Truck Casks		Rail Casks	
	Steel-Lead-Steel	Steel-DU-Steel	Steel-Lead-Steel	Monolithic Steel
10	79	123	220	216
30	161	211	256	231
60	289	341	314	265
400	793	775	766	562

6.5 Sensitivity Discussion

Three-year high burn-up spent fuel was used for the thermal calculations in contrast with the ten-year average burn-up fuel that will typically be transported in the casks of the design types considered. The conservatism introduced by this assumption is large. For example, thermal loads for a three-year high-burn-up PWR fuel assemblies are on the order of 2.8 kilowatts, while the ten-year average-burn-up fuel assembly produces less than 600 watts of decay heat. With thermal calculations, the three-year high burn-up spent-fuel assumption leads to conservative risk estimates, because more rapid heating means that seal degradation and rod burst temperatures can be reached with fires of shorter duration.

While conservative, the calculations in the report do not include some secondary effects that would need to be considered if the cask designs were to be used for transport of three-year high-burn-up fuel. For example, the use of the cask inner-surface temperature to estimate rod burst-rupture temperature would not be acceptable with three-year spent fuel. This is because the overall temperature increase from the cask inner surface to highest fuel rod temperature could reach several hundred degrees Celsius for multiple three-year assemblies. For the ten-year average burn-up fuel, the temperature increase from the cask inner surface to the center of the fuel assemblies is typically less than 100°C [6-5]. Inspection of the calculations used in this section demonstrated that the use of the three-year high burn-up fuel in the risk calculations adequately compensates for the neglect of the temperature increase between the cask inner surface and the fuel rods for ten-year average burn-up fuel.

In an additional conservatism, the phase change of the neutron shield material at the outside of the cask is also neglected. The neutron shield can be water or a solid hydrogenous material. For this analysis water is assumed. The neutron shield material thermal properties are changed in the calculation instantaneously at the start of the fire from water to air. In the calculations, when the neutron shield is voided instantaneously, the inner surface of the neutron shield rapidly reaches fire temperature within one to two minutes. When the liquid remains, the increase to boiling temperature and the boiling of the water limits the temperature increase of the cask interior to 100°C for several minutes, depending on the amount of water left in the collision-damaged shield. For example, for a full shield on the SDUST cask, the boiling of water would limit the shield-inner-surface temperature to near 100°C for about 20 minutes at the start of a fire. Similar conservative results would be obtained if a solid neutron shield material were to be used.

To estimate the conservatism introduced with the three-year spent fuel assumption, an additional 1000°C long-duration fire calculation was performed for the most rapidly responding cask, the steel-DU-steel truck cask. The time to reach the seal degradation temperature of 350°C, given in Table 6.5 for three-year high burnup fuel, increased from 0.59 hours to 0.86 hours. Similarly, the time to reach the rod burst temperature of 750°C increased from 1.96 to 2.68 hours. This indicates that time-to-temperature increases on the order of 30 to 50 percent are anticipated if ten-year average burn-up fuel is used in calculations rather than three-year high burnup fuel. The effect of this change on overall risk probabilities is much smaller, however, because for the assumed fuel, times-to-failure already fall into the low-probability tail of the fire duration probability distribution curves (see Tables 7.26 and 7.27). Increasing these times simply places the probabilities further out on the tail of these distribution curves.

6.6 Summary

Thermal analysis of the generic casks provided input for risk analysis of characteristic times at which the casks may undergo elastomeric seal failure or rod burst/rupture. This analysis was conservative for the following reasons:

- The casks, although similar in dimension to casks available from manufacturers, were not optimized for their thermal response.
- The analysis assumed that the casks were uniformly engulfed in the fire.
- The fire temperature was assumed to be 1000°C.
- The water in the neutron shield was immediately replaced by air at the onset of the long duration fire to simulate fluid loss as a result of puncture of the neutron shield.

6.7 References

[6-1] PATRAN Thermal User Guide and Model Description Manual (http://www.macsch.com/support/support.html).

[6-2] A. G. Croff, "ORIGEN2: A Versatile Computer Code for Calculating the Nuclide Compositions and Characteristics of Nuclear Materials," *Nuclear Technology* **62**, p. 335 (1983).

[6-3] B. V. Karlekar, and R. M. Desmond, *Engineering Heat Transfer,* West Publishing Co., 1977.

[6-4] G. D. Raithby, and K. G. T. Hollands, "A General Method of Obtaining Approximate Solutions to Laminar and Turbulent Free Convection Problems," A*dvances in Heat Transfer,* Academic Press, NY, 1974.

[6-5] G. W. Thomas and R. W. Carlson, "Evaluation of the Use of Homogeneous Fuel Assemblies in the Thermal Analysis of Spent Fuel Storage Casks," UCRL-ID-134567, Lawrence Livermore National Laboratory, Livermore, CA, July, 1999.

Page intentionally left blank